# ALL-ORDER CORRECTIONS TO HIGGS BOSON PRODUCTION IN ASSOCIATION WITH JETS

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We present a new framework for calculating multi-jet observables. The framework is based on the factorisation of scattering amplitudes in the kinematical limit of large invariant mass between all particles. We show that by constraining the analyticity of scattering amplitudes away from this limits, we get good agreement order by order with the full, fixed order perturbative calculation at the low orders where these are available, and therefore get firm predictions on the all-order behaviour. As an example, we study Higgs boson production through gluon fusion in association with at least two jets at the LHC.

## 1 Introduction

Achieving the full potential of the LHC will challenge our understanding and description of events with multiple jets. A detailed understanding and description of the multi-jet predictions arising from the Standard Model (SM) is necessary in order to fully disentangle this contribution from that which might arise from much sought-after extensions of the Standard Model.

The true complication of each observed jet in terms of its constituent hadrons can currently only be described within the context of a parton shower and hadronisation model, as implemented in e.g. Ref. [1,2,3]. However, while obtaining a good description of the *structure* of each jet, the underlying soft and collinear resummation often underestimates the *rate* and *hardness* ($p_\perp$-spectrum) of multi-jet samples[4]. Matching procedures[5,6,7] can ensure that the description of a given process contains at least the full tree-level. Virtual corrections (and the resulting weighting of samples with varying jet multiplicity) are, however, estimated using only the Sudakov factor from the shower, which arises from the requirement of unitarity of the parton shower.

In this contribution, we will describe results obtained in an approach, which sums perturbative corrections to the hard scattering matrix element to all orders, but considers corrections of a different origin than that of the soft and collinear logarithms of the parton shower. Instead of focusing on the emission under small invariant masses, we will focus on the limit of hard, wide-angle emission. The goal is to achieve an all-order exclusive description of the leading radiative corrections (real and virtual) for the formation of extra jets, and not be concerned with the description of the internal structure of each jet, which we will leave for a later matching with a parton shower.

## 2 Building Blocks for All-Order Results

The approximation, which eventually allows us to construct an exclusive (i.e. differential in the momenta of all particles), all-order resummation of the hard scattering matrix element, is

based on keeping only the leading contribution to scattering amplitudes in the limit where the invariant mass $s_{ij}$ between all particles is large. The QCD radiative corrections to the basic $2 \to 2$ partonic process (or $2 \to Wjj\ldots$) can then be calculated in this limit. In terms of the rapidities $y_i$ and transverse momenta $p_{\perp,i}$ of each particle, this *Multi-Regge Limit* is written as

$$y_0 \gg y_1 \gg \ldots \gg y_{n+1}; \quad |p_{i\perp}| \simeq |p_{i+1\perp}|, \qquad (1)$$

where obviously $y_0 \gg y_1$ really means $y_0 - y_1 \to \infty$. In fact, the leading contribution to the tree-level matrix elements of *all* scattering processes can be calculated in this strict limit (and sub-leading contributions are suppressed by one power of $s_{ij}$ in the square of the matrix element). This MRK limit of the matrix elements is reproduced by a set of Feynman rules consisting of just one Feynman diagram for each rapidity ordering of particles. This one Feynman diagram consists of a string of gluon propagators connecting effective vertices[8,9] like e.g. the non-local *Lipatov vertex*

$$C^{\mu_i}(p_a, p_b, q_i, q_{i+1}) = \left[ -(q_i + q_{i+1})^{\mu_i} - 2\left(\frac{\hat{s}_{ai}}{\hat{s}_{ab}} + \frac{\hat{t}_{i+1}}{\hat{s}_{bi}}\right) p_b^{\mu_i} + 2\left(\frac{\hat{s}_{bi}}{\hat{s}_{ab}} + \frac{\hat{t}_i}{\hat{s}_{ai}}\right) p_a^{\mu_i} \right], \qquad (2)$$

here described for the scattering process $p_a\, p_b \to p_0 \cdots p_n$, where $\hat{s}_{ai} = 2p_a \cdot p_i$ etc., and $\hat{t}_i = q_i^2$ is the propagator associated with the $i^{\text{th}}$ connecting gluon. In fact, the leading virtual corrections can be parametrised to all orders by replacing the $1/q_i^2 \to 1/q_i^2 \exp(\hat{\alpha}(q_i)(y_{i-1} - y_i))$ in the propagators.

So if these effective Feynman rules results in an approximation of the scattering amplitude which reproduces the known MRK limit of the full scattering amplitude, why not just use this limit instead of the (slightly) more involved effective Feynman rules? The point is that we would like an approximation for the *inclusive* corrections to all orders, i.e. without having to require large rapidity separations between *each and every* set of particles. By using the effective Feynman rules, we can ensure that aside from reproducing the correct MRK limit, the amplitudes fulfill certain requirements when applied away from the MRK limit (obviously, any phase space point relevant to the LHC is specifically *away* from the exact MRK limit). Firstly, the amplitudes which arise from these effective Feynman rules are gauge-invariant, i.e. satisfies the Ward identity $k.M = 0$ *exactly* for each gluon of any (on-shell) momentum $k$, not just in the MRK limit. Secondly, the full kinematic dependence is kept in the divergences arising from the propagators of the connecting $t$-channel gluons (i.e. there is no limit taken in the kinematic invariants arising); see Ref.[10,11] for more details.

By also capturing the leading (in $\log(s_{ij}/t_i)$) contribution to the virtual corrections, it is straightforward to organise the cancellation of the infra-red poles between the real and virtual corrections, see e.g. Ref.[10]. The resulting amplitudes are sufficiently simple that they can be evaluated to any (necessary) order in $\alpha_s$, and the phase space integration is efficiently implemented following the procedure of Ref.[12]. The end result is an *inclusive* (in the sense of including the emission of any number of gluons) calculation, which is *exclusive* in the momenta of all particles. Therefore, any analysis (jet-algorithm, etc.) can be implemented on the output of the resummation.

## 3 Higgs Boson plus Multiple Jets

This resummation scheme was first applied to the process of Higgs Boson production through gluon fusion in association with at least two jets[10,11]. This process is particularly interesting when a large rapidity difference between two jets occurs. Firstly, it allows for an extraction of the CP structure of the ttH-coupling[13]. Secondly, it is necessary to understand the process in details, since it is a background to the extraction of the coupling of the Higgs boson to Z/W in
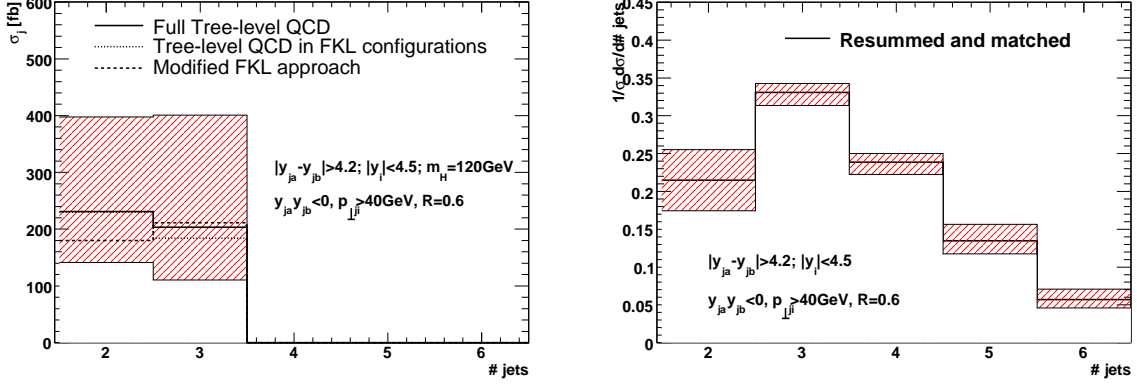
Figure 1: **Left:** The cross section for hjj and hjjj obtained using MadGraph, compared with the result obtained using the effective Feynman rules, allowing all-order resummation. **Right:** The relative jet rates in the fully resummed and matched event sample.

Higgs boson production through weak boson fusion [14]. This process therefore naturally lends itself to a treatment based on the phase-space assumptions of Eq. (1).

After constructing a set of Feynman rules which are sufficiently *simple* to allow all-order results to be constructed, the next step for any resummation programme should be to verify that the rules are also sufficiently *accurate* that whatever is summed will resemble the perturbative series for whatever process is claimed to be resummed. On Fig. 1(left) we compare the $\alpha_s^4$ and $\alpha_s^5$ cross sections for hjj and hjjj (jets defined with kt-algorithm, $p_\perp > 40$GeV) production respectively, between our approximation (allowing all-order results to be obtained) and the full tree-level QCD results (obtained using MadGraph[15]), within a standard set of *weak-boson fusion*-cuts, and with a scale choice equal to a Higgs mass of 120GeV. The red bands indicate the scale uncertainty. It is clear that the approximation is sufficiently accurate in describing the hard emission that it is worthwhile constructing a resummation based on them. This holds true also for kinematic distributions, see Ref.[10]. Furthermore, in the final formulation the Higgs boson plus two and three jet results are matched to full tree-level accuracy. On Fig. 1(right), we show the relative contribution from various exclusive jet states within the resummed and matched result for inclusive Higgs boson production in association with at least two jets. Again, the red bands indicate the scale uncertainty in the relative jet rates in the resummed result. We see that within these cuts, the exclusive two-jet rate will account for only roughly 17-25% of the cross section for Higgs boson production in association with two or more jets, with the higher jet rates accounting for the rest.

The inclusive (i.e. containing virtual and real-emission corrections to all orders) nature of the resummation allows one to study the dependence on the details (like rapidity-range and transverse momentum cut) of a central jet veto. Such jet vetos are intended to suppress the gluon-fusion contribution to the hjj-channel. As an example, we show in Fig. 2 the cross section in the resummed and matched calculation, when apart from the cuts mentioned on the figure, a requirement is imposed that

$$\forall j \in \{\text{jets with } p_{j\perp} > p_{\perp,\text{veto}}\} \setminus \{a, b\} \; : \; \left| y_j - \frac{y_a + y_b}{2} \right| > y_c, \qquad (3)$$

where jets $a, b$ are the most forward/backward hard jet of transverse momentum larger than 40GeV. For a transverse momentum cut of 40GeV, the result for $y_c \to \infty$ is obviously what would be called the exclusive two-jet rate of the resummed and matched calculation. It is seen that with a veto as hard as 40GeV on further jets, the cross section is reduced to about 100fb
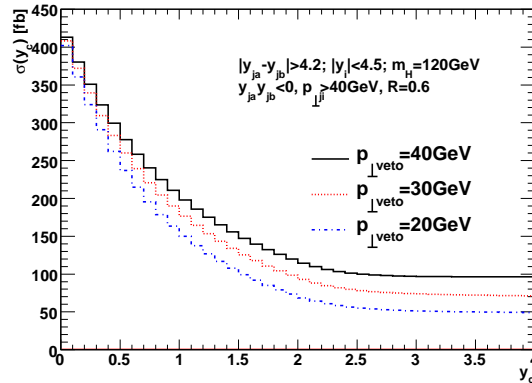
Figure 2: The cross section for Higgs boson production in association with at least two jets, as a function of the parameters of a veto on extra jet activity.

(with the scale choices made in Ref.[10]), which is less than half of the tree-level prediction for hjj within the same cuts. This promises well for central jet vetos as a method of suppressing gluon fusion contribution to hjj within the weak boson fusion cuts.

## 4  Conclusions

We have very briefly described the ideas behind a resummation scheme, which captures the effects of hard emission resulting in the formation of observable jets, and discussed example analyses. A partonic event generator based on this formalism for Higgs boson production in association with jets can be downloaded `http://andersen.web.cern.ch/MJEV`.

## References

1. Torbjorn Sjostrand, Stephen Mrenna, and Peter Skands. A Brief Introduction to PYTHIA 8.1. *Comput. Phys. Commun.*, 178:852–867, 2008.
2. M. Bahr et al. Herwig++ Physics and Manual. *Eur. Phys. J.*, C58:639–707, 2008.
3. T. Gleisberg et al. Event generation with SHERPA 1.1. *JHEP*, 02:007, 2009.
4. J. Alwall et al. Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions. *Eur. Phys. J.*, C53:473–500, 2008.
5. S. Catani, F. Krauss, R. Kuhn, and B. R. Webber. QCD Matrix Elements + Parton Showers. *JHEP*, 11:063, 2001.
6. Leif Lonnblad. ARIADNE version 4: A Program for simulation of QCD cascades implementing the color dipole model. *Comput. Phys. Commun.*, 71:15–31, 1992.
7. Michelangelo L. Mangano, Mauro Moretti, Fulvio Piccinini, and Michele Treccani. Matching matrix elements and shower evolution for top- quark production in hadronic collisions. *JHEP*, 01:013, 2007.
8. V. S. Fadin, R. Fiore, M. G. Kozlov, and A. V. Reznichenko. Proof of the multi-Regge form of QCD amplitudes with gluon exchanges in the NLA. *Phys. Lett.*, B639:74–81, 2006.
9. A. V. Bogdan and V. S. Fadin. A proof of the reggeized form of amplitudes with quark exchanges. *Nucl. Phys.*, B740:36–57, 2006.
10. Jeppe R. Andersen, Vittorio Del Duca, and Chris D. White. Higgs Boson Production in Association with Multiple Hard Jets. *JHEP*, 02:015, 2009.
11. Jeppe R. Andersen and Chris D. White. A New Framework for Multijet Predictions and its application to Higgs Boson production at the LHC. *Phys. Rev.*, D78:051501, 2008.
12. Jeppe R. Andersen. On the role of NLL corrections and energy conservation in the high energy evolution of QCD. *Phys. Lett.*, B639:290–293, 2006.
13. G. Klamke and D. Zeppenfeld. Higgs plus two jet production via gluon fusion as a signal

at the CERN LHC. *JHEP*, 04:052, 2007.

14. V. Hankele, G. Klamke, D. Zeppenfeld, and T. Figy. Anomalous Higgs boson couplings in vector boson fusion at the CERN LHC. *Phys. Rev.*, D74:095001, 2006.

15. Johan Alwall et al. MadGraph/MadEvent v4: The new web generation. *JHEP*, 09:028, 2007.